Electric Aircraft Propulsion System

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This report specifies the purpose, assembly, operation, and data collection of a testing apparatus to characterize small electric aircraft propulsion systems designed for commercial use. This apparatus was constructed with the goal of determining overall system characteristics and efficiencies. The apparatus was pushed to a safety limit as deemed by advisor John Dunning and the results of the experiment were an output power of 3.2kW (25% of max rated power) and a system efficiency of 58.6%, both of which occurred at 2200 RPM. Currently the apparatus needs improvement. It should have an upgraded structure to mount to (instead of the table in use now), a wind tunnel large enough to fit the system inside (enabling propeller efficiency calculation), and a more robust and less noisy DAQ system. With all those things in place this system could have a major impact on Cal Poly's Aerospace Department, because as of right now it does not have a single electric aircraft propulsion system.

Acknowledgements:

John Dunning,
for his much needed guidance and supervision.

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I. Introduction

The purpose of CREATT is to explore alternate transportation technologies. Operating under the program is the Electric Aircraft Propulsion System which is used to investigate alternate transportation technologies in the aviation field. There exist four categories in aviation that warrant a look at alternate approaches. Figure 1 provides a visual of the four categories. Starting at the small scale and moving upward is small UAVs, Ultralite Recreational Aircraft, General Aviation, and Large Scale Aircraft. This project focuses on the Ultralite Recreational Aircraft category; it provided an easily accessible commercial product to conduct research on. The actual product settled on was from Electric Aircraft Corporation called the Electraflyer Trike. Specific components will be discussed in depth later in the report.

Figure 1: UAV[1], Ultralite[2], General Aviation[3], Large Scale Aircraft[4]

II. Objectives

The objective of the Electric Aircraft Propulsion System is to characterize a commercially available product. This is achieved by measuring thrust, torque, battery pack voltage and current, motor voltage and current, as well as propeller RPM. This data will yield experimental performance metrics that can be compared to the system's advertised performance. While this is the specific goal for each run of the experiment, the long term overarching goal is to create a teaching tool for Cal Poly's Aerospace Engineering department. The lab would be beneficial because the department does not currently have an electric aircraft propulsion laboratory.

III. Apparatus & Procedure

The components of the experimental system were purchased from Electraflyer.com. The Electraflyer Trike's propeller, motor, controller, and battery pack compose the electric aircraft propulsion system to be characterized. The apparatus itself is composed of parts from McMaster Carr, Thomson Industries Inc., Buck Algonquin, FUTEK, Nation Instruments, and Omega.

Figure 2: Push propeller used in experiment.

Figure 2 shows the propeller of used in this system. It is a 4ft diameter, carbon fiber composite, folding pusher. There are a few different models that can be purchased but this one gives a good starting point; it is affordable and easy to install. The electric motor used in conjunction with the push propeller is shown in Fig. 3.

Figure 3: Electric Motor Used in Experiment.

The motor used is 25lbs, 8in diameter, DC brushless permanent magnet electric motor. The controller used to operate the electric motor is a Kelly Controller model CD117 and can be found inside the controls enclose in Fig. 4.

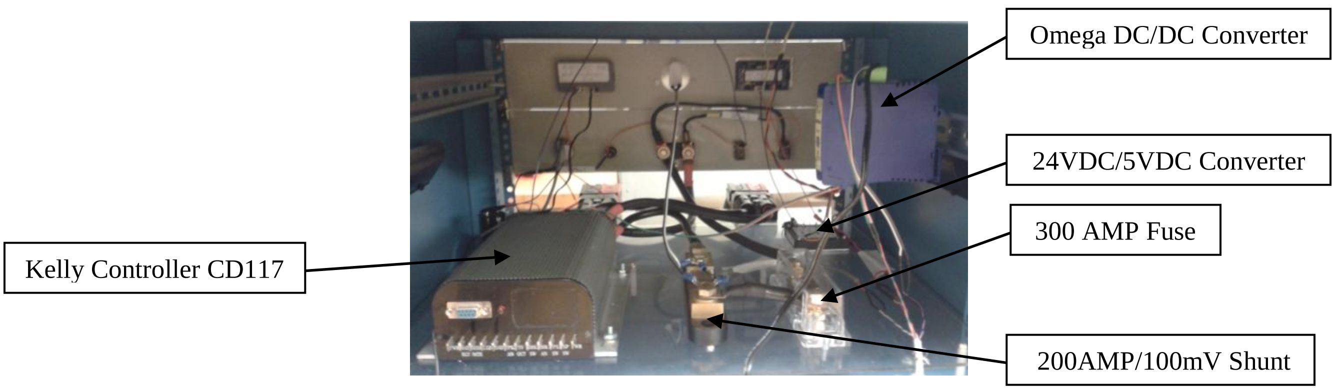

Figure 4: Controls Enclosure back view. (internals)

The Omega DC/DC Converter was used in conjunction with a not shown wall plug Omega 120VAC/24VDC converter. This allowed the controls enclosure to have a 24V bus to power the Omega DC/DC Converter, the 24VDC/5VDC Converter (giving a 5V bus to power the display screens), and the FUTEK sensor. Unfortunately the wall plug AC/DC converter introduced a significant amount of noise into the system. Because the system is built to take data, the next iteration of this laboratory would need to improve the specific components so the data is less noisy and easier to record. To record the current flowing through the system a shunt was used. As a safety measure the controls enclosure also included a 300A fuse.

The battery pack is made up of six sub-packs. Each sub-pack is made up of 15 cells; 5 in parallel and those in series with two more making three in total. Each cell is 3.7V and 10Ah yielding sub-pack of 11.6V and 50Ah. There are six sub-packs that are to be connected in series. Therefore, the total pack has 72V nominal, 3.5kWh, and 50Ah. Figure 5 shows a battery sub-pack inside a protective casing.

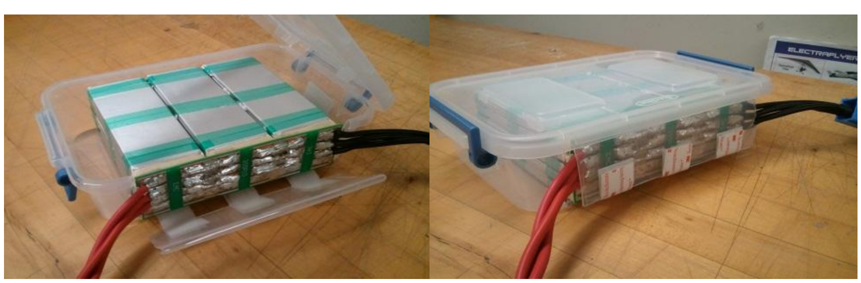

Figure 5: Battery sub-pack inside protective case.

This protective casing option was chosen because the batteries are not going to be under load for long periods of time reducing the need for active or passive cooling. This setup also allows a flexible modular approach that reduces the assembly and disassembly time. Figure 6 shows the thrust and torque FUTEK sensor coupled with the shaft and motor saddle.

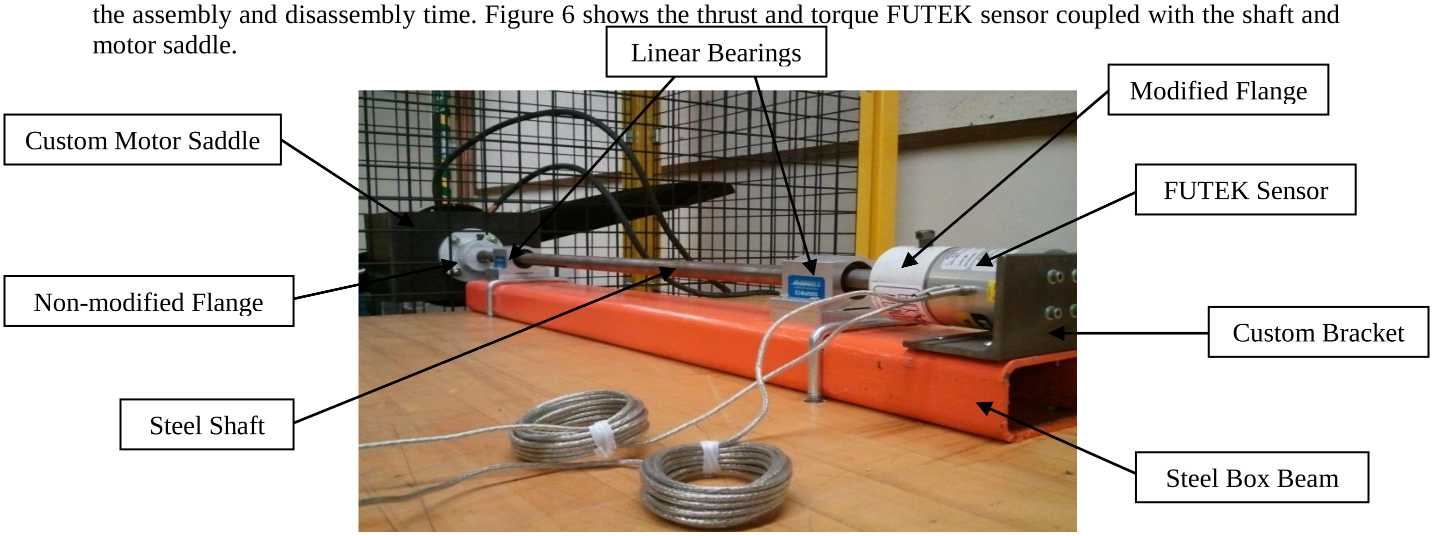

Figure 6: FUTEK thrust and torque sensor.

The sensor simultaneously measures thrust and torque with 500lbs and 500in-lbs capacity, respectively. It provides a simple and easy way to extract precise data from the apparatus. To get the data from the sensor a National Instruments Data Acquisition (DAQ) card was purchased and installed. Unfortunately this created unforeseen problems including the range of allowable input voltages and more importantly, the wall plug noise created within the system greatly reduced the accuracy of the incoming measurements. After much trial and error an Agilent 34972A, as seen in Fig. 7, was used in place of the National Instrument DAQ.

Figure 7: Agilent DAQ used for tests.

A Hall Effect sensor was going to be used in conjunction with a magnet attached to the motor shaft to measure the propeller's RPM. This approach proved unsuccessful. Instead, a strobe tachometer was used. Now that the individual components that make up both the apparatus and the electric propulsion system have been identified it is important to step through the assembly of the apparatus, because assembling it out of order will cause problems.

Apparatus Set Up Procedure

1) Take box beam and bolt down the rear bracket, rear spacer, rear linear bearing, front spacer, and front linear bearing.
   a) Hang the box beam off of a table with the 12 smaller holes facing up.

b) The two groups of 4 holes that are closer together should be on the side hanging off the table.
c) Take the rear bracket and set it on top of the 4 holes that are the farthest off the table.
d) Insert 4 M4X20 (4mm diameter by 20mm long) bolts into the 4 rear bracket/box beam holes that line up. The head of the bolts should rest on the top of the rear bracket.
e) Take a 7mm nutdriver and put a 4mm hex nut into it.
f) With the 4mm hex nut resting inside the 7mm nutdriver, rest a 4mm washer on top of that.
g) Have one hand holding the head of the bolt against the rear bracket and the other hand carefully holding the washer, hex nut, and nutdriver assembly.
h) Now put the nutdriver assembly through the larger holes in the bottom of the box beam and carefully screw the washer and hex nut onto the bolt.
i) Do the same for the other three holes and later in the assembly procedure use a screwdriver to hold the top of the bolt head to get a tight fit while screwing the nut.

2) Do this same procedure for the rear spacer and rear linear bearing.
   a) Instead of 4MX20 use 4 M4X40 that have hex heads.
   b) Mate the rear spacer to the rear linear bearing by matching the faces of the parts which have been written on.
   c) Insert the bolts into the matching holes and the assembly onto the rear 4 holes next to the 4 rear bracket holes.
   d) Now follow steps 1)e)→i) noting that a 7mm wrench must be used instead of a screw driver for final tightening but do not do the final tightening yet.
3) The process for assembling the front spacer and front linear bearing is the same as 2).
   a) The only difference is the other end of the box beam is now hanging off the table
   b) But, the front is still the front that was already defined, as well as, the left and right.
4) Prepare box beam for table
   a) Align the box beam assembly so the smaller holes (where all the previous components were installed) are on top. Put it in between the 4 holes that have been drilled into the table. Get the front edge of the box beam to b flush with the edge of the table.
   b) Put the 2 U-bolts around the box beam as if it was going to be bolted down. This will be bolted down later after other parts have been assembled.
5) Fasten the rear flange to the FUTEK torque and thrust sensor.
   a) Orient the 2 parts such that the machined side of the flange touches the bottom side of the sensor.
   b) Recalling the previous labeling convention we want to align our parts' holes so that the flange's set screws are facing up (top) and right. The sensor needs to have the two wire ports facing left.
   c) Screw the two together with 4 5/32"X2" bolts, using a Philips head screwdriver to tighten.
6) Fasten rear flange/sensor assembly to the rear bracket.
   a) Use 4 4mm washers and 4 M4X15 hex screws.
   b) Use a 9/64 hex key (Allen wrench) to tighten.
7) Assemble propeller safety shroud.
   a) The 4 main pieces of the safety shroud form a rectangle. One out of the two wider pieces will have a few parts of the mesh cut out. That piece goes closest to the table so that the shaft can run through it. Only assemble three of the four pieces so that the rest of the apparatus can be set up before securing the propeller safety shroud.
8) Combine the front flange and the shaft.
   a) Slide the shaft into the front flange, matching the long shaft key slot to the flange's key slot.
   b) Take the long shaft key and fit it into the gap created from the two key slots.
   c) Tighten the two set screws.
   d) The end of the shaft should be flush with the flange as well as the key.
9) Take the front flange/shaft assembly and slide it through the propeller safety shroud, the front and rear linear bearings, and attach it to the rear flange.
   a) The side of the shaft with the shorter key slot is to be slid from the front to the rear through the linear bearings.
   b) Once the shaft gets through the rear linear bearing, align the shaft key slot to the rear flange's key slot.
   c) Push the shaft through the rear flange so it comes into contact with the recess in the sensor.
   d) Insert the shorter shaft key into the gap created from the shaft flange's key slots.
   e) Be sure to put the key in so that the face that has some material removed is facing away from the shaft's key slot.

f) Also, the side that has had some material removed is to be on the opposite side of the sensor. Orienting the key this way allows the key to fit even though one of the screws is in the way. It will be a tight fit but it does fit. Push hard.

10) Now, tighten down the front and rear linear bearings as well as the rear bracket.'
11) Now, bolt the box beam assembly to the table.
    a) Bolt the box beam to the table using the 2 U-bolts and their 4 washers and hex nuts.
    b) A 9/16 socket wrench can be used to tighten it.
    c) Tighten it until the washers bend; this is what will stop the test rig from literally flying away.
12) Bolt the motor saddle to the front flange.
    a) Use 4 lock washers, hex nuts, and hex bolts with a crescent wrench and a 9/16 socket wrench to tighten.
13) Screw the motor into the motor saddle.
    a) Use 4 lock washers and hex bolts with a ½ socket wrench to tighten.
14) Bolt the propeller to the motor using the long propeller key, the bolt holder, the bolt and washer. Use a 13mm socket wrench.

Data Recording Procedure

1) Connect the shunt wires, Omega DC/DC Converter scaled battery pack voltage wires, FUTEK Mz torque wires, and FUTEK Fz thrust wires to the Agilent multiplexer card in different channels.
2) Make sure the controls enclosure has the precharge, panel, and main switch OFF (down position, down position, key removed)
3) Plug the Omega AC/DC wall plug into a standard 120V 60Hz wall outlet.
4) Measure each battery cell and record.
    a) A damaged or unexpectedly low cell could create problems for the entire battery pack.
    b) If there are cells outside of 3.80-3.60V then do not proceed.
5) Connect the battery sub packs into the main pack.
    a) Make sure that the flow is always positive to negative or negative to positive, do not connect positive to positive or negative to negative.
6) Connect the main battery pack into the controls enclosure.
    a) Now connect the main battery pack's positive end to the controls enclosure's positive battery in Anderson Connecter. Connect the main battery pack's negative end to the controls enclosure's negative battery in Anderson Connecter.
7) Connect the motor positive and negative Anderson Connecters to the controls enclosure's motor out Anderson Connecter.
8) Make sure the Agilent unit is powered on and monitoring the first channel of interest.
9) Make sure the throttle knob is at 0% (turn counter clockwise).
10) Turn ON the precharge switch and wait for the voltage display to stop changing.
11) Turn ON the panel switch and wait for the voltage display to stop changing.
12) Plug in and turn the main switch ON.
13) Cycle through the Agilent channels of interest and record the steady state values.
14) Slowly turn the throttle knob clockwise until the propeller starts moving.
15) With the propeller slowly moving, turn on the strobe tachometer and adjust the speed to match the propeller (the prop should appear stationary.)
16) Increase the throttle a bit at a time and adjust the strobe tachometer to match. At each interval record Mz (torque), Fz (thrust), pack voltage, shunt voltage, and RPM.
    a) Be careful that the table that the apparatus is attached to does not start moving due to the thrust. During an experiment the table started to move at approximately 1740 RPM. That equates to about 1.3kW of shaft output power. The motor can handle 13kW. Be careful.
17) After achieving the desired RPM and power data, the same process is done in reverse to safely shutdown and disconnect the system.

IV. Analysis

Once the data is collected, the first step is to calculate output power in horsepower as shown in Eq. 1.[5]

$$Power_{hp} = \frac{RPM*2\pi*T}{396000} \tag{1}$$

Where T is measured in in-lb. This number must then be converted to watts, the preferred unit of power for electric motors. For the purposes of this report, the conversion from horsepower to Watts will be done using the standard Metric system identity

$$1\ hp = 735.5\ W \tag{2}$$

This is done as shown in Eq. 3.

$$Power_{out_W} = P_{hp} * 735.5 \tag{3}$$

And from this a direct calculation for $P_{motor\ out_W}$ can be calculated

$$Power_{motor\ out_W} = \frac{735.5\pi * RPM * T}{198000} \tag{4}$$

To calculate motor efficiency, this value is compared to the input power which is simply calculated from measured data as shown in Eq. 5

$$Power_{motor\ in} = V * A \tag{5}$$

Efficiency is defined as

$$\eta_{motor} = 100 * \frac{Power_{motor\ out_W}}{Power_{in}} \tag{6}$$

These calculations were taken from a user manual supplied by Aveox, the motor manufacturer for the Raven UAV system.[6]

V. Results

After setting up the apparatus, a power supply with a maximum output power of 1kW was used to assess the system's capability to function properly. Figure 9 shows the variation of torque and shaft output power when RPM is changed.

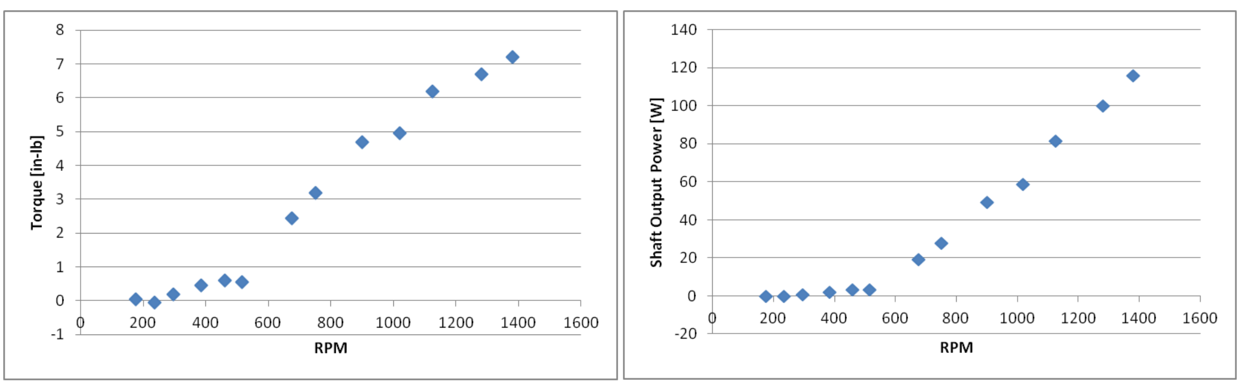

Figure 8: Torque and Shaft Output Power as a function of RPM using 1kW power supply.

As stated earlier, this test was done with a power supply that maintains constant voltage and adjusts the current that the system receives as the RPM is increased. The data is not perfectly linear. Although there are many factors that contribute to the data's deviation from a more linear relationship the most influential of those is the noise coupled with the human error of reading data from that noise. When a stable RPM was achieved each channel of the Agilent DAQ would be hand cycled through and the values recorded by eye. It was easier to see that an increase had happened than it was to see exactly what that new number was. Hence, after the transient low speed values it can be seen that the data becomes closer to the expected trend of linearity. This test was stopped at approximately 1400 RPM because the power draw was maxing out the 1kW power supply. The apparatus did not show any signs of danger or instability at this max power RPM so it was decided to use the battery pack to operate at higher power settings.

Once the battery pack was assembled and attached to the controls enclosure, the system was spun up to the previous data's limit of close to 1400 RPM. Using the higher power battery pack allowed for the system to be tested up to 2200 RPM. Figure 9 shows the battery pack voltage and current draw during the test and Fig. 10 shows the resulting torque and output power of this test.

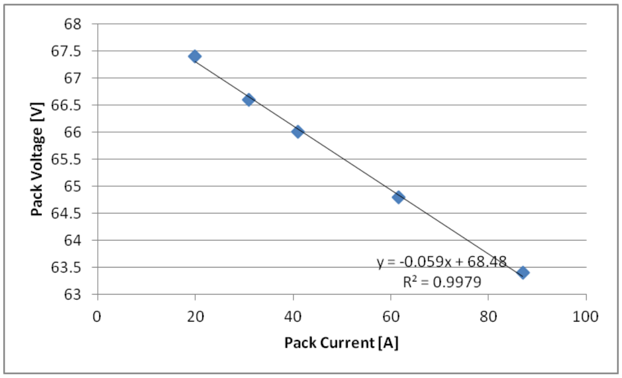

Figure 9: Battery Pack voltage as a function of current draw.

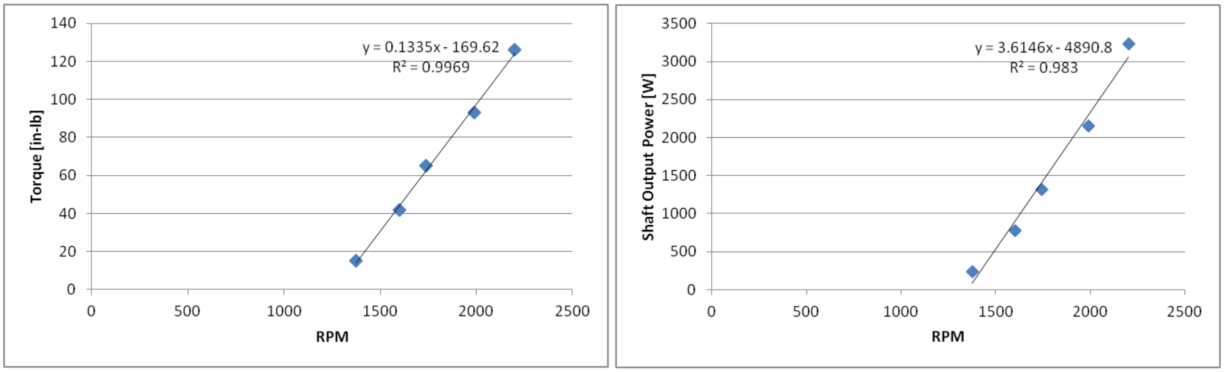

Figure 10: Torque and Shaft Output Power as a function of RPM using battery pack.

The battery pack behaved as expected. The more current drawn from the pack the lower the voltage charge. The test was not done at higher RPMs because the table was not bolted to the floor and just the weight of the table would not be enough to keep the system from moving as it created more thrust. It can be seen from the above figure that the torque and output power from the system is almost linear with respect to RPM. Recall that the motor used is rated to 13kW of power output, so these tests only managed to get to 25% of that rated max. This means that the results may not show an entirely accurate model of how the system will act at higher power settings. The data collected should be analyzed as the system's low power performance. Figure 11 shows the system's efficiency for the data gathered.

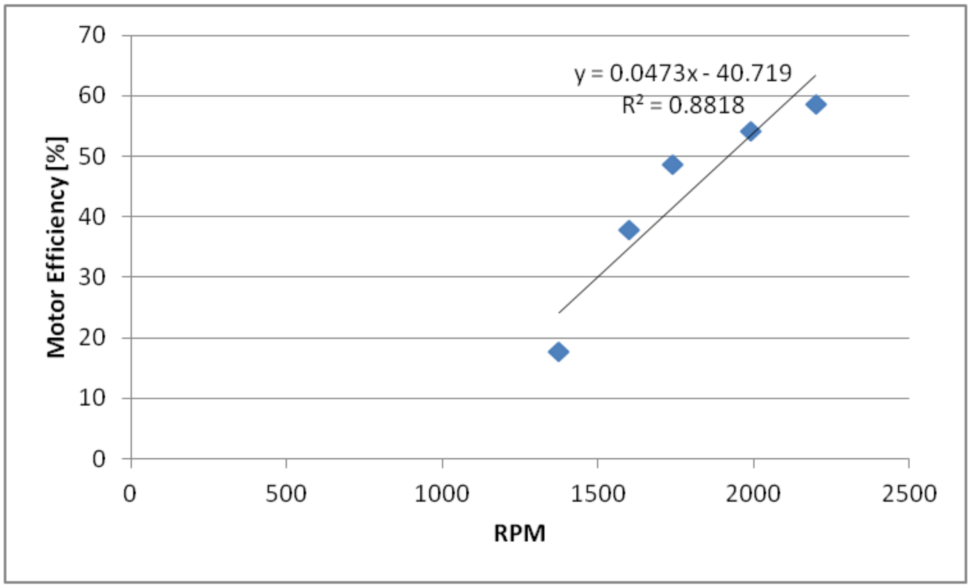

Figure 10: Motor Efficiency as a function of RPM.

It can be seen that the efficiency is not as linear of a relationship, with respect to RPM, as the torque and output power were. The first three data points have a much steeper trend and it appears that the system efficiency will reach its maximum efficiency quickly. But, the last two points indicate a shallower climb to the system's max efficiency. Because the system is only running in the first 25% of rated output power it is more likely that the last two points' trend is a more accurate model.

Unfortunately, the system is too large to physically fit inside Cal Poly's 3'x4' subsonic wind tunnel, therefore only static tests of the system could be done. This fact equates to meaningless propeller efficiency being meaningless because calculating prop efficiency includes free stream velocity. With free stream velocity being equal to zero so must the prop efficiency.

Overall, an output power of 3.2kW and system efficiency of 58.6% was achieved using the test rig in a static condition. If this system was to be improved, it should have an upgraded structure to mount to (instead of the table in use now), a wind tunnel large enough to fit the system inside, and a more robust and less noisy DAQ system. With all those things in place this system could have a major impact on Cal Poly's Aerospace Propulsion class, because as of right now they do not have a single electric aircraft propulsion system.

References

[1]Raven UAV Picture, army-technology.com

[2]ElectrFlyer Trike Picture, bowenairport.com

[3]Cri Cri Aircraft Picture, txchnologist.com

[4]Boeing Large Scale Electric Aircraft Concept Picture, txchnologist.com

[5]Bourassa, James, Rosz, John, "Calculating Horsepower, RPM, and Torque," WISC-Online, 2004. [http://www.wisc-online.com/Objects/ViewObject.aspx?ID=ENG17504. Accessed 12/6/11.]

[6]Unknown, "AVX-50BL10 50V, 10A Brush / Brushless Power Amplifier Data Sheet and Setup Guide," Aveox, Inc.

Raw Data

Data collection 3-27-12

	Preload	Throttle ON	more 1	more 2	more 3	more 4	more 5	more 6	more 7	more 8	more 9	more 10	more 11	more 12
Mz [V]	-0.696	-0.697	-0.695	-0.7	-0.705	-0.708	-0.707	-0.745	-0.76	-0.79	-0.795	-0.82	-0.83	-0.84
Fz [V]	-2.6	-2.63	-2.64	-2.64	-2.64	-2.65	-2.62	-2.8	-2.77	-2.71	-2.63	-2.65	-2.6	-2.63
PackV [V]	1.97	2.03	2.04	2.04	2.05	2.05	2.05	2.04	2.04	2.035	2.03	2.02	2.02	1.84
PS V [V]	60	60	60	60	60	60	60	60	60	60	60	60	60	55
PS C [A]	0	0.6	0.79	1	1.4	1.85	2.25	3.9	4.8	7.4	9.9	13	18.6	24.7
Shunt V [V]	0	0.0002	0.0003	0.0004	0.0006	0.0009	0.0011	0.0019	0.0023	0.0036	0.0049	0.0064	0.0092	0.0123
RPM [1/min]	0	175	235	295	385	460	515	675	750	900	1020	1125	1280	1380
Mz [in-lb]	-34.8	-34.85	-34.75	-35	-35.25	-35.4	-35.35	-37.25	-38	-39.5	-39.75	-41	-41.5	-42
Fz [lb]	-130	-131.5	-132	-132	-132	-132.5	-131	-140	-138.5	-135.5	-131.5	-132.5	-130	-131.5
PackV [V]	59.1	60.9	61.2	61.2	61.5	61.5	61.5	61.2	61.2	61.05	60.9	60.6	60.6	55.2
Shunt C [A]	0	0.4	0.6	0.8	1.2	1.8	2.2	3.8	4.6	7.2	9.8	12.8	18.4	24.6
		subtract off preload for Mz & Fz												
Mz [in-lb]		0.05	-0.05	0.2	0.45	0.6	0.55	2.45	3.2	4.7	4.95	6.2	6.7	7.2
Fz [lb]		-1.5	-2	-2	-2	-2.5	-1	-10	-8.5	-5.5	-1.5	-2.5	0	-1.5
PackV [V]		60.9	61.2	61.2	61.5	61.5	61.5	61.2	61.2	61.05	60.9	60.6	60.6	55.2
Shunt C [A]		0.4	0.6	0.8	1.2	1.8	2.2	3.8	4.6	7.2	9.8	12.8	18.4	24.6
Power In [W]		24.36	36.72	48.96	73.8	110.7	135.3	232.56	281.52	439.56	596.82	775.68	1115.04	1357.92
Power Out [W]		0.102111678	-0.13712	0.688524	2.021811	3.220894	3.305501	19.29911	28.00777	49.3637	58.92136	81.39759	100.0811	115.9522

Data collection 3-29-12

	Preload	Throttle O	more 1	more 2	more 3	more 5	more 6	Stopped
Mz [V]	-0.791	-0.77	-1.09	-1.63	-2.09	-2.65	-3.31	-0.646
Fz [V]	-2.629	-2.63	-2.58	-2.52	-2.5	-2.4	-2.3	-2.6
PackV [V]	68.9	68.8	67.4	66.6	66	64.8	63.4	67.4
Shunt V [V]	0.000019	0.00051	0.01	0.0155	0.0205	0.0308	0.0435	0.00002
RPM [1/min]	0	325	1375	1600	1740	1990	2200	0
Mz [in-lb]	-39.55	-38.5	-54.5	-81.5	-104.5	-132.5	-165.5	-32.3
Fz [lb]	-131.45	-131.5	-129	-126	-125	-120	-115	-130
PackV [V]	68.9	68.8	67.4	66.6	66	64.8	63.4	67.4
Shunt C [A]	0.038	1.02	20	31	41	61.6	87	0.04
		subtract off preload for Mz & Fz						
Mz [in-lb]	0	-1.05	14.95	41.95	64.95	92.95	125.95	-7.25
Fz [lb]	0	-0.05	2.45	5.45	6.45	11.45	16.45	1.45
PackV [V]	68.9	68.8	67.4	66.6	66	64.8	63.4	67.4
Shunt C [A]	0.038	1.02	20	31	41	61.6	87	0.04
Motor Power in [W]		70.176	1348	2064.6	2706	3991.68	5515.8	2.696
Motor Power out [W]	0	-3.98236	239.8895	783.2841	1318.851	2158.58836	3233.614	0
Motor Efficiency [%]	#DIV/0!	-5.67481	17.79596	37.93878	48.73803	54.0771895	58.62457	0